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Instantaneous 3-Phases Power as Dignified Signal by Analysis of Electrical Equipment Energy Efficiency and Malfunction Diagnosis

ELECTROMAGNETIC COMPATIBILITY (EMC) AND POWER QUALITY

Commonly 3-phases active power, reactive power and distortion power are used by analysis of energy efficiency of electrical equipment with non-sinusoidal, asymmetrical and unsteady loads. Decomposition of 3-phases currents and voltages to symmetrical components of positive, negative and null sequences on fundamental frequency and on high harmonics is using often.

Electrical equipment (for example – various kinds of electric drivers) malfunction diagnosis is often realized by current and voltages instantaneous values and their spectrums changes.

Appearance of current and voltage digital analyzers among measuring instruments permits to use for analysis also dignified signal of instantaneous 3-phases power in investigated network:

$$p_{3ph}(t) = u_a(t) \cdot i_a(t) + u_b(t) \cdot i_b(t) + u_c(t) \cdot i_c(t) . \tag{1}$$

It is supposed in (1) phase voltages $u_a(t)$, $u_b(t)$ и $u_c(t)$ are measured relatively to neutral conductor in 4-wire network or relatively to earth in 3-wire network.

Parameter $p_{3ph}(t)$ has almost constant value in networks with symmetrical and linear load, when voltages and currents of fundamental frequency only are present (ideal case). Power $p_{3ph}(t)$ value is changing slowly due to unavoidable changing of load. Any deflection from these ideal condition leads to appearance of variable components in instantaneous 3-phases power. Variable components are evidence of system unbalancing which is caused by high harmonics, asymmetrical harmonics (incl. first and null components), fast changing of currents and voltages. Power $p_{3ph}(t)$ wave and spectrum analysis gives the important information about research object.

Instantaneous power $p_{3ph}(t)$ on averaging (processing) time T_{av} can be decomposed to Fourier row with pick out of constant component P_0 and harmonics discrete row P_Ω

with relative frequencies $\Omega=f_\Omega/f_{av}$, divisible by base decomposition frequency $f_{av}=1/T_{av}$. The resolution by relative frequencies determination depends on T_{av} value and currents and voltages sampling rate. Frequencies f_Ω with the step up to 0.1 Hz could be determine for certain by sampling rate up to 20 kHz and T_{av} ≤10 s. The highest harmonic with 10 kHz frequency can be determine in this case. It is based on the authors experience by using of the digital multi-channel oscillograph-analyzer «NEVA-IPE» (the producer is Energosoyuz LTD, St. Petersburg).

Instantaneous 3-phases powers frequency and amplitude spectrums analysis allows to discover their anomalies, to carry out of equipment diagnosis and to forecast probability of various kinds of failures which can be eliminate in time. Diagnosis by $p_{3ph}(t)$ signal has certain advantages over diagnosis by current spectrum method, which is apply widely, because $p_{3ph}(t)$ signal reflects energy matter of processes.

Frequency spectrum of $p_{3ph}(t)$ signal differs from currents and voltages spectrums. For example, generated in instantaneous 3-phases power harmonics order $n_p = f_{n_p}/f_1$ by symmetrical and non-distortion voltages and by integer harmonics in currents decomposed to positive and negative sequences are shown in the table below. Zero-sequence harmonics doesn't exist in instantaneous 3-phases power. Negative and positive current harmonics generate positive and negative instantaneous 3-phases power harmonics accordingly. The formula for relative frequencies n_p determination can be presented as

$$n_p = n \pm 1, \tag{2}$$

where "+" should be used for negative sequence harmonics and "-" for positive sequence harmonics.

Current harmonic $n=f_n/f_1$	Current harmonic sequence	Instantaneous 3-phases power harmonic $n_p = f_{n_p}/f_1$
$n=0$	-	$n_p=1$
$n=1$	Positive	$n_p=0$ ($P_0=const$)
	Negative	$n_p=2$
$n=2$	Positive	$n_p=1$
	Negative	$n_p=3$
$n=3$	Positive	$n_p=2$
	Negative	$n_p=4$
$n=4$	Positive	$n_p=3$
	Negative	$n_p=5$
…………………………………………………………………………………		

Instantaneous 3-phases power spectrum approach to continuous when integer harmonics, inter- and subharmonics are present in currents and voltages.

Existing of variable components in $p_{3ph}(t)$ signal is evidence of unbalanced system and of existing of active power exchange interphase flows. Their intensity on chosen processing time T_{av} can be determine by instantaneous 3-phases power variable component effective value $P_{\sim eff}$ after total signal $p_{3ph}(t)$ effective value $P_{3ph\ eff}$ calculation:

$$P_{\sim eff} = \sqrt{P_{3ph\ eff}^2 - P_0^2}\ . \qquad (3)$$

Process unbalance increases in transient behaviour of electrical equipment.

The series of $p_{3ph}(t)$ signals and their spectrums examples in networks with non-linear industry electrical installations.

Power $p_{3ph}(t)$ of electric arc furnace (EAF) with transformer 85 MVA is shown on Fig.1a. Black curve $P_{av}(t)$ is calculated by averaging of instantaneous 3-phases power $p_{3ph}(t)$ on time periods 0.02 s. Apparently power $p_{3ph}(t)$ changes fast within the limits ±45% from average value. At that this changes has a main frequency 100 Hz and it is evidence that negative sequence currents of EAF dominate. Frequency 50 Hz rises above in $p_{3ph}(t)$ signal in some time moments by big values of aperiodic components of EAF currents. The first part of instantaneous 3-phases power spectrum on chosen process interval T_{av}=0.2 s is shown on Fig.1b. Harmonics with the step f_{av}=5 Hz are fixed there. Harmonics in 0..30 Hz range have biggest amplitude with orders $\Omega=f_\Omega/f_{av}$=0..6 (against f_{av}) and n_p=0..0.6 (against f=50 Hz).

Instantaneous 3-phases power $p_{3ph}(t)$ for non-linear and symmetrical electric installations with predominant valve converters doesn't contain 100 Hz frequency but $p_{3ph}(t)$ signal has significant fluctuations. Fig.2a,b demonstrate previous statement. Measurements results of power roll mill on 10 kV bus bar of one metallurgical plant there are shown. Instantaneous 3-phases power has fluctuations with predominant of even harmonics with orders 12, 24, 36, 58, 60 and 62. Harmonics with 58 order and more in this case caused by resonance processes in supply network.

It is especially important to have information about signal $p_{3ph}(t)$ measured directly on the electric motor clamps. Amplitude-frequency spectrum of this signal can be interpret as frequency distortion that influences on electric drive axle. Getting and analysis of this kind of distortion spectrums can be used as a basis of defect identification and estimation of motor reliability methods by start-and-adjustment operations.

Appearance of anomalistic spikes in $p_{3ph}(t)$ curve on repetition cycle by steady states after accumulation of information about bond of $p_{3ph}(t)$ fluctuations with concrete failure can use for malfunction diagnosis. New results can be achieved in this field.

The example of instantaneous 3-phases power and its spectrum on nonsynchronous engine clips with P_{nom}=18.5 kW are shown on Fig.3. The engine has reduced-current start equipment. Intensive power fluctuations on shaft are existed as a result of angle control. Amplitude of 6-th harmonic equals 30% from average active power by start or 54 % from engine nominal power.

Another example of engine power $p_{3ph}(t)$ measurement is presented on Fig.4b conformably to scheme on Fig.4a where ventilator electric drive with frequency speed control is shown. It is used two frequency converters with 6-phase invertors supplying two synchronous engines with nominal power 2.5 MW. Two engines have one shaft with ventilator. Frequency f_2 on inverters output can change in the range 0..45 Hz. Twelve-phase mode of operation for supply network and power fluctuations reducing on ventilator shaft is provided due to 30 electrical degree displacement on transformers and 30 electrical degree displacement between engine 1 and engine 2. Fluctuating instantaneous 3-phases power on engine 1 ($p_1(t)$) and engine 2 ($p_2(t)$) shafts and summary instantaneous 3-phases power on ventilator shaft $p_\Sigma(t)=p_1(t)+p_2(t)$ by mode when f_2=25 Hz (with cycle duration equals 0.04 s) are shown. Harmonics with frequencies 25, 300 and 600 Hz ($n_p=f_{np}/f_{25}$=1,12 and 24) determine in $p_\Sigma(t)$ spectrum (see Fig.5). Harmonic with frequency 150 Hz determines in $p_1(t)$ *u* $p_2(t)$ spectrum. This spectrum changes by speed rotation control of ventilator shift. Existing of intensive fluctuations of active power and proportional to it moment on various part of ventilator shift should take into consideration by reliability evaluation of this electric drive.

Conclusions

Presented considerations about instantaneous 3-phases power properties as energy signal may be essential for evaluation of nonlinearity and asymmetrical degree of electrical installations, for operation stability inspection and for equipment condition diagnosis.

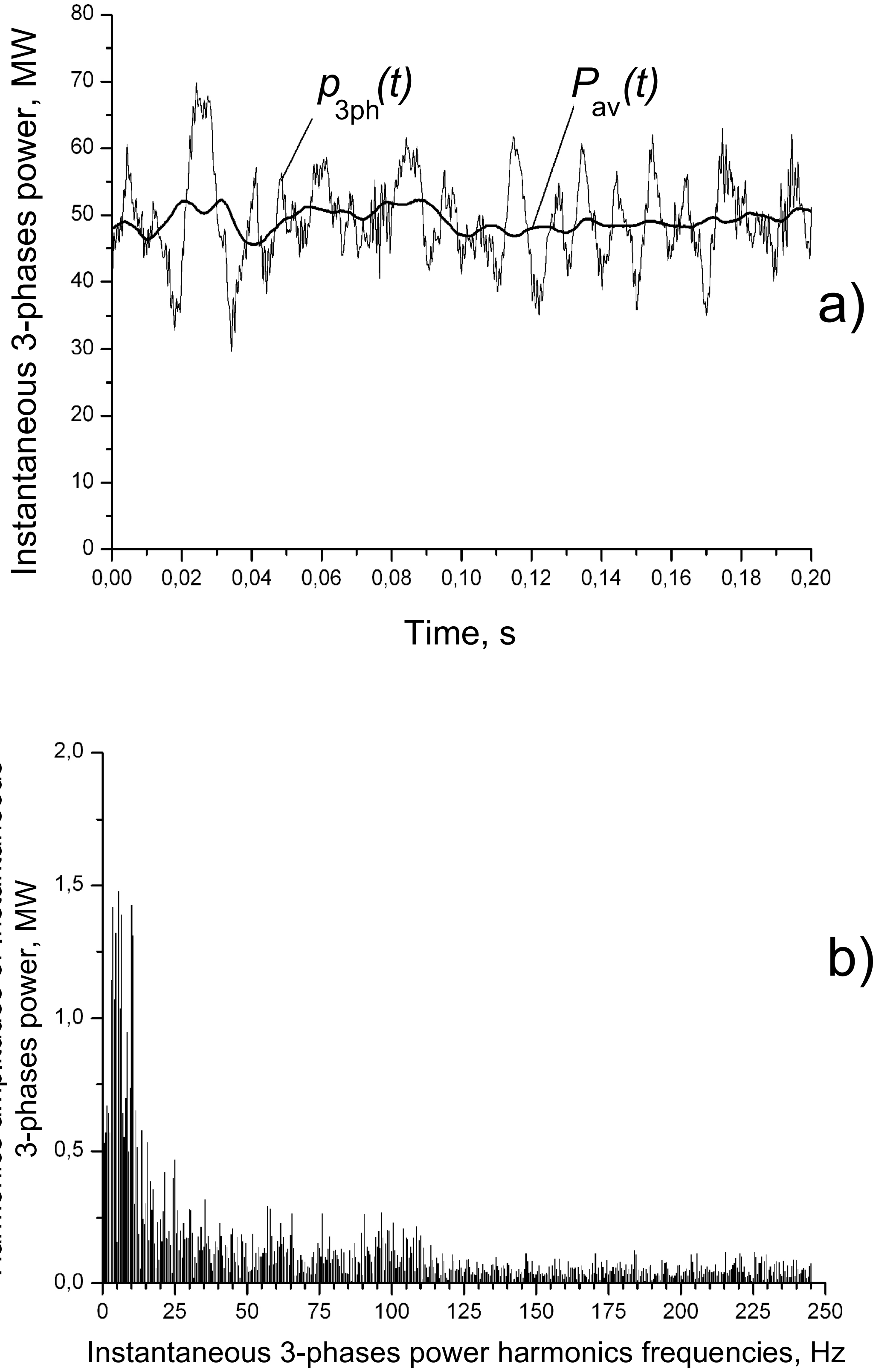
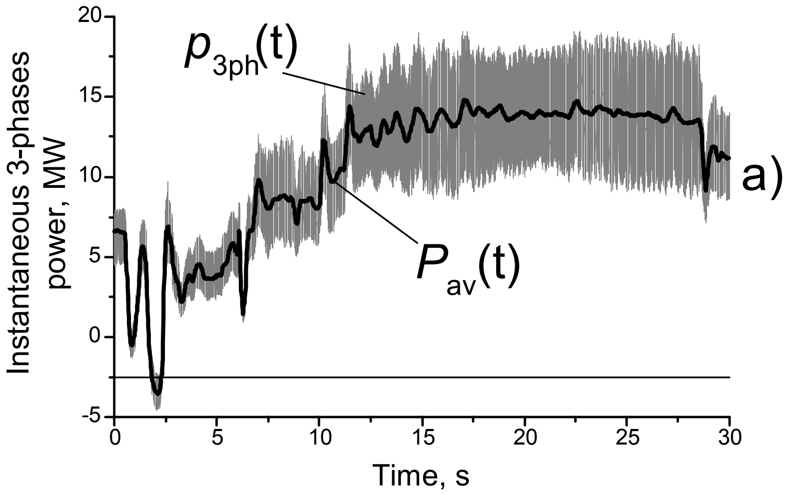
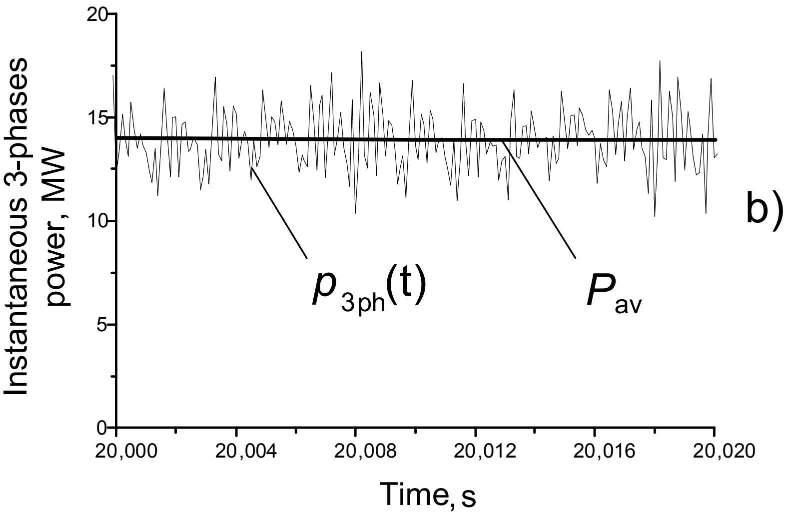


Fig.1. *Instantaneous 3-phases power of electric arc furnace $p_{3ph}(t)$ (a) and its spectrum (b).*





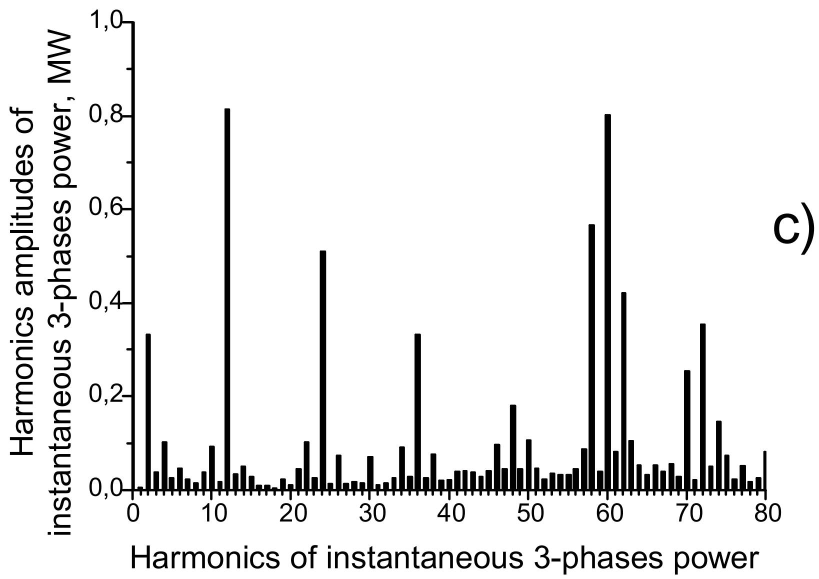
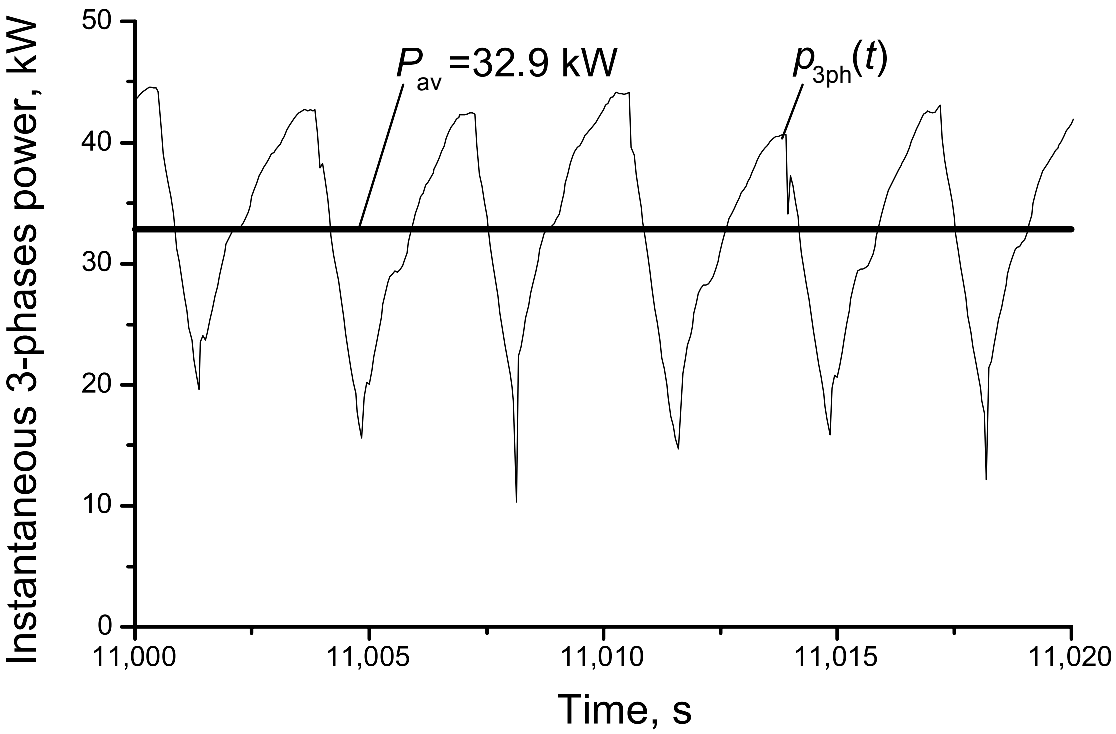


Fig.2. *Instantaneous 3-phases power of roller mill electric drive $p_{3ph}(t)$ (a), instantaneous 3-phases power with time scale zoom (b) and its spectrum (c).*



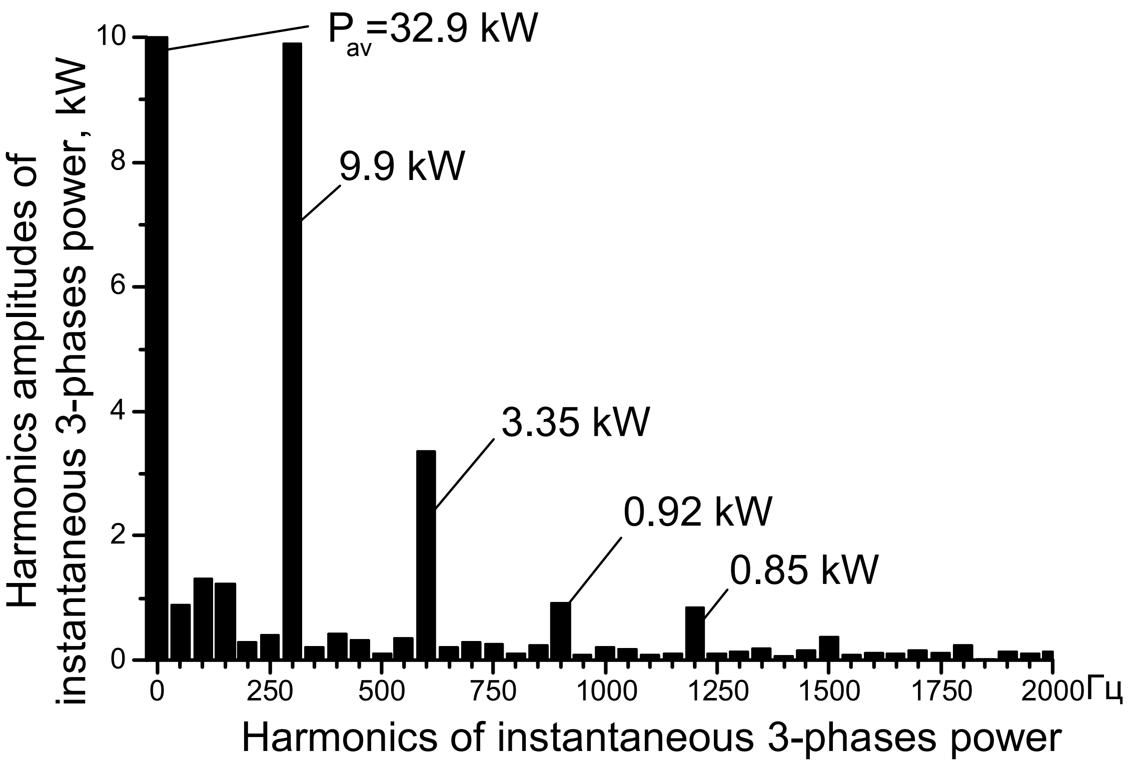


Fig.3. *Instantaneous 3-phases power $p_{3ph}(t)$ and its stectrum by nonsynchronous engine start with currrent reducing due to angle control.*

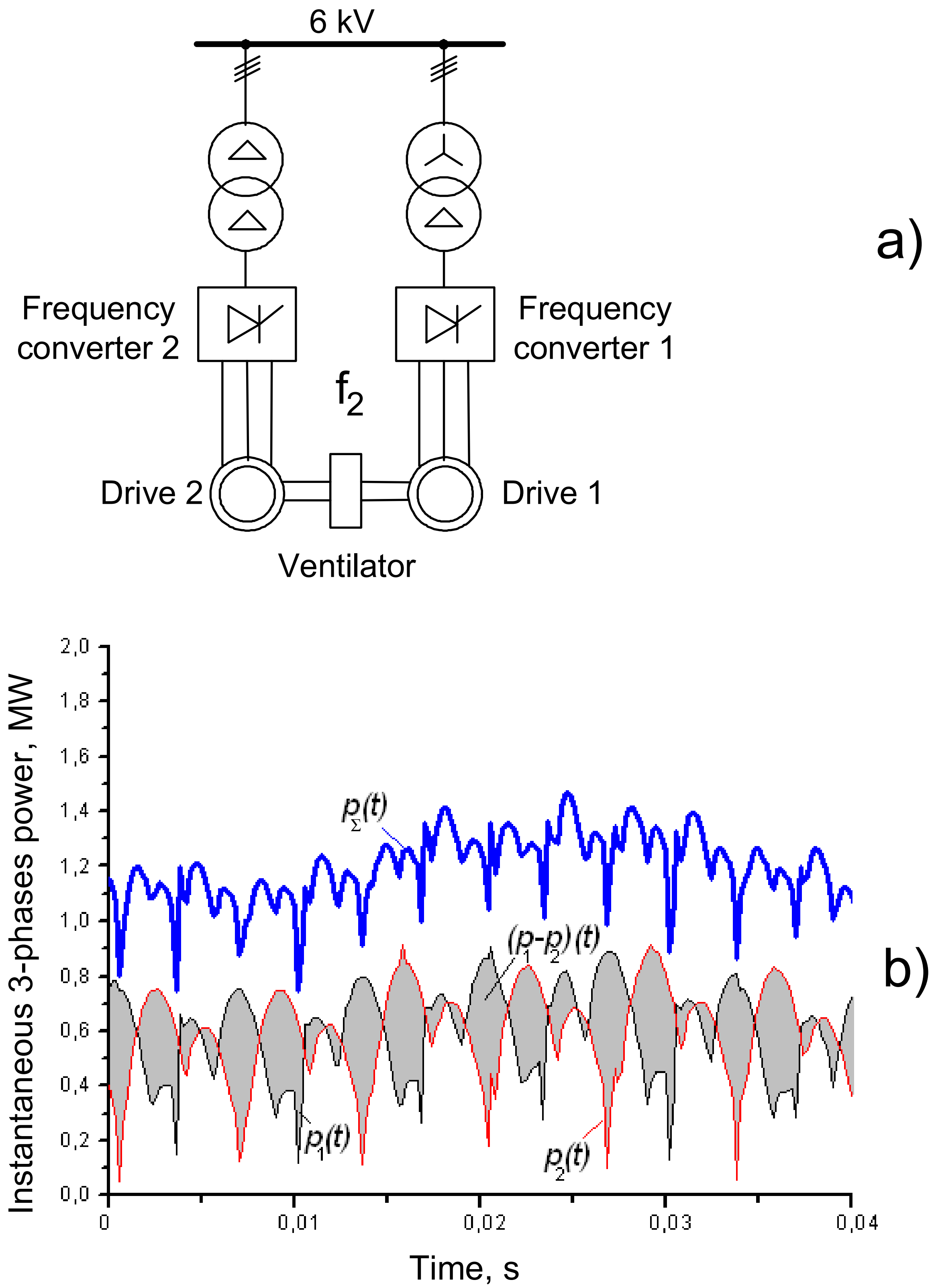


Fig.4. *a) Ventilator scheme*
b) Instantaneous 3-phases power $p_1(t)$ and $p_2(t)$ on synchronous drives shafts, summary power $p_\Sigma(t)=p_1(t)+p_2(t)$, variable component of power $p_1(t)–p_2(t)$, which influence on shaft.

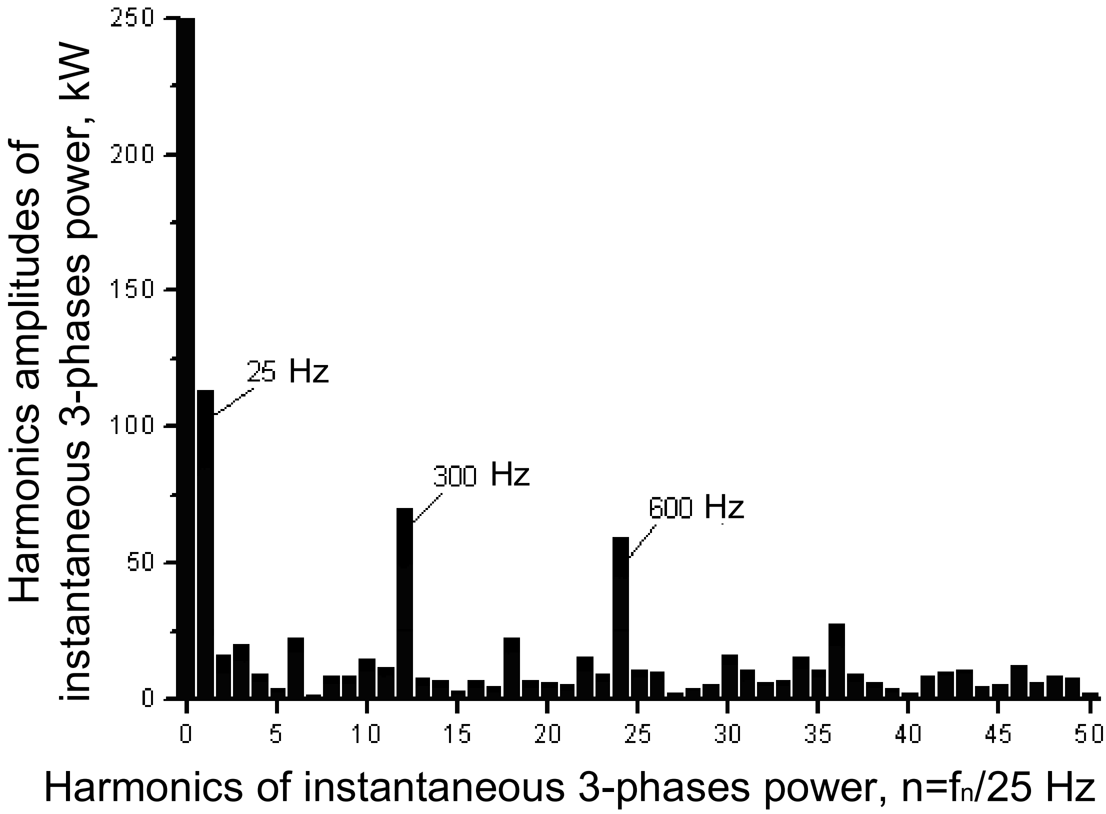


Fig.5. *Summary power $p_{\Sigma}(t)=p_1(t)+p_2(t)$ spectrum.*

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